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The heavy ion cooler-storage-ring project (HIRFL-CSR) at Lanzhou

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Abstract

HIRFL-CSR, a new ion Cooler-Storage-Ring (CSR) project, is the post-acceleration system of the Heavy Ion Research Facility in Lanzhou (HIRFL). It consists of a main ring (CSRm) and an experimental ring (CSRe). From the HIRFL cyclotron system the heavy ions will be accumulated, cooled and accelerated in the CSRm, then extracted fast to produce radioactive ion beams (RIB) or highly charged heavy ions. Those secondary beams will be accepted and stored by the CSRe for many internal-target experiments with electron cooling.

Keywords: Project; Cooler; Storage ring; e-cooling; Lattice

1. Introduction

From May 1993 to November 1996, a new plan was proposed [1,2] to upgrade the Heavy Ion Research Facility in Lanzhou (HIRFL) [3] with a multi-functional Cooling Storage Ring (CSR) forming a HIRFL-CSR accelerator system shown in Fig. 1. This will greatly enhance the performances of HIRFL for those researches by using Radioactive Ion Beams (RIB) and high-Z heavy ion beams in the fields of nuclear physics and atomic physics. In July 1998, the Chinese central government approved this plan, and on December 10, 1999, the CSR project was started. The period beginning from 2000 to the summer of 2001 is the stage of the building construction, design optimization and prototype experiments. The machine fabrication is to be from 2001 to 2003, and 2004 is the installation and tuning time. The whole desired construction time is nearly 5 years, and the total budget is about 300 million Chinese yuan.

2. General descriptions

2.1. Outline

HIRFL-CSR [4] is a multi-purpose CSR system that consists of a main ring (CSRm), an

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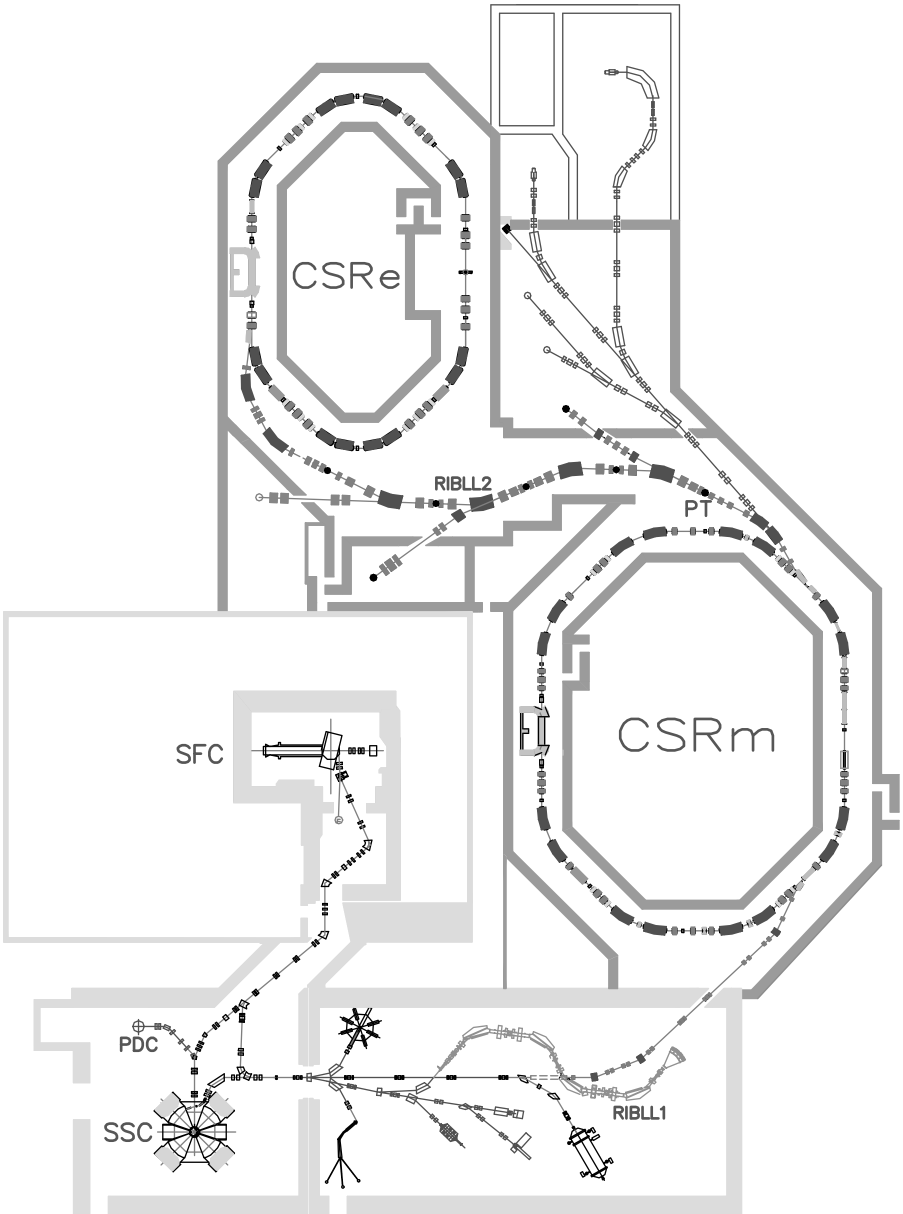


Fig. 1. Overall layout of the HIRFL-CSR complex.

experimental ring (CSRe), and a radioactive beam line (RIBLL2) to connect the two rings, shown in Fig. 1. The two existing cyclotrons SFC ($K = 69$) and SSC ($K = 450$) of the HIRFL will be used as its injector system. The heavy ion beams with the energy range of 8–30 MeV/u from the HIRFL will be accumulated, cooled and accelerated to the high-energy range of 100–400 MeV/u in the main ring, and then extracted fast to produce RIB or highly charged heavy ions. The secondary beams (RIB or highly charged heavy ions) will be accepted and stored by the experimental ring for many internal-target experiments or high-precision spectroscopy with beam cooling. On the other hand, the beams with the energy range of 100–900 MeV/u will also be extracted from CSRm by using slow extraction or fast extraction for many external-target experiments.

Two electron coolers located in the long-straight sections of CSRm and CSRe, respectively, will be used for the beam accumulation and cooling. One internal target in the long-straight section of CSRe will be used for nuclear physics and highly charged state atomic physics, and many external targets of CSRm will be used for nuclear physics, cancer therapy study and other researches.

2.2. Major parameters

The beam parameters and the major machine parameters of the CSR system are listed in Table 1.

3. Operation scheme

3.1. Normal operation mode

CSR is a double ring system. In every operation cycle, the stable-nucleus beams from the injectors are accumulated, cooled and accelerated in the main ring (CSRm), then extracted fast to produce RIB or highly charged ions. The experimental ring (CSRe) can obtain the secondary beams once for every operation cycle. The accumulation duration of CSRm is about 10 s. Considering the ramping rate of magnetic field in the dipole magnets to be 0.1–0.4 T/s, the acceleration time of CSRm will be nearly 3 s. Thus, the operation cycle is about 17 s.

In CSRe, two operation modes will be adopted. One is the storage mode used for internal-target experiments or high-precision spectroscopy with electron cooling. Another one is the

Table 1
Major parameters of the CSR

	CSRm		CSRe
Circumference (m)	161.00		128.80
Ion species	Stable nuclei: C–U, RIB($A<238$)		Stable nuclei: C–U, RIB($A<238$)
Max. energy (MeV/u)	900 (C^{6+}), 400 (U^{72+})		600 (C^{6+}), 400 (U^{90+})
Intensity (particles)	10^5–10^9 (stable nuclei)		10^3–10^9 (stable nuclei, RIB)
Time structure of beam	1 Pulse/cycle for fast extraction, 0.1–5 s for slow extraction		Quasi-continuous beam
Experiment mode	External target		Internal target
$B_{\rho_{max}}$ (Tm)	10.64		8.40
B_{max} (T)	1.4		1.4
Ramping rate (T/s)	0.1–0.4		0.1–0.4
Repeating circle (s)	~ 17 (~ 10 s for accumulation)		
Acceptance			Normal mode
A_h (π mm mrad)	200 ($\Delta P/P = \pm 0.15\%$)		150 ($\Delta P/P = \pm 0.5\%$)
A_v (π mm mrad)	30		75
$\Delta P/P$ (%)	1.25 ($\varepsilon_h = 50\,\pi$ mm mrad)		2.6 ($\varepsilon_h = 10\,\pi$ mm mrad)
e-Cooler			
Ion energy (MeV/u)	8–50		25–400
Cooling length (m)	4.0		4.0
RF system	Acceleration	Accumulation	Capture
Harmonic number	1	16, 32, 64	1
f_{min}/f_{max} (MHz)	0.24/1.7	6.0/14.0	0.5/2.0
Voltages (n $\times$ kV)	1×7.0	1×20.0	2×10.0
Vacuum pressure (mbar)	6.0×10^{-11}		6.0×10^{-11}

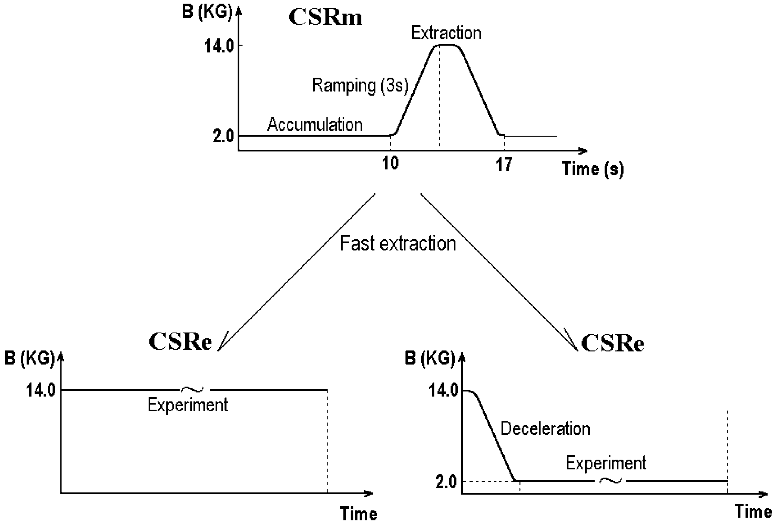


Fig. 2. Magnetic field exciting procedure of CSR.

deceleration-storage mode used for atomic-physics experiments. Fig. 2 shows the magnetic field exciting procedure of the two rings.

In every cycle, the circulating beams in CSRe can be used for bombarding the internal target continuously. Therefore, the quasi-continuous beams could be obtained at the internal target. In fact, CSRe is the beam stretcher of CSRm. Fig. 3 shows the time structure of the CSR two rings in such a quasi-continuous-beam operation mode.

3.2. Injector system

The existing HIRFL [3] facility will be used as the injector system of CSR. It consists of two cyclotrons, the main accelerator Separated Sector Cyclotron (SSC, $K = 450$) and the pre-accelerator Sector-Focusing Cyclotron (SFC, $K = 69$). The light heavy ions, example C, N, O etc., can be injected into CSRm directly from SFC without the acceleration of SSC, but those heavy ions ($A > 40$) should be accelerated by the combination of SFC and SSC before the injection. The mean extraction radii of SFC and SSC are 0.75 m and 3.20 m, respectively. The beam parameters of HIRFL as the injector system of CSRm are shown in Table 2.

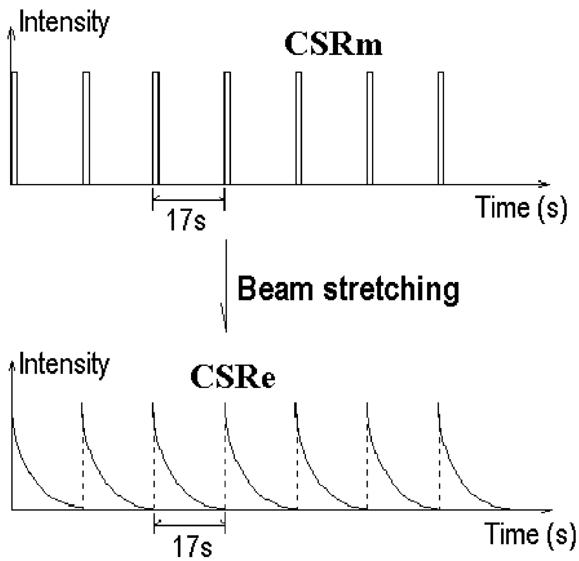


Fig. 3. Time structures of the CSR beams.

3.3. Beam accumulation

While heavy ion beams from HIRFL are injected into CSRm, the beam lifetime should be sufficiently long for the beam accumulation in CSRm. Referring to the actually measured spectra of residual gases [5,6], in the case where the average pressure of CSR is assumed to be

Table 2
Beam parameters from the injectors

Ions	Energy (MeV/u)	F_{Rev} (MHz)	Harmonic number	Intensity (pps)
SFC injection				
$^{12}C^{5+}$	10	9.248	1	3×10^{12}
$^{16}O^{7+}$	10	9.248	1	2×10^{12}
$^{20}Ne^{8+}$	10	9.248	1	1×10^{12}
$^{40}Ar^{14+}$	8	8.284	1	8×10^{11}
$^{40}Ca^{14+}$	8	8.284	1	4×10^{11}
Emittance $<10\pi$ mm mrad ($\pm\sigma$)			$\delta P/P<\pm0.15\%(\pm\sigma)$	
SSC injection (before stripping)				
$^{58}Ni^{14+}$	25	3.380	4	2×10^{11}
$^{84}Kr^{21+}$	25	3.378	4	2×10^{11}
$^{129}Xe^{28+}$	20	3.033	4	1×10^{11}
$^{181}Ta^{35+}$	15	2.162	4	8×10^{9}
$^{208}Pb^{36+}$	12	2.162	4	8×10^{9}
$^{238}U^{37+}$	10	2.162	4	8×10^{9}
Emittance $<10\pi$ mm mrad ($\pm2\sigma$)			$\delta P/P<\pm0.15\%(\pm2\sigma)$	
Phase width $\sim\pm5^\circ$			Phase stability $\sim\pm0.5^\circ$	

6.0×10^{-11} mbar, the residual gas composition will be 85% of H_2 and 15% of N_2 and CO. According to the calculation [7], the REC (radiative electron capture) process in the electron cooler restricts the lifetimes of light heavy ions (C–Kr) in CSRm, while the electron capture from the residual gas molecule dominates the lifetimes of heavy ions (Xe–U), and the beam loss caused by Coulomb scattering becomes negligible. In conclusion, the beam lifetimes (>15 s) are longer than the time taken for beam accumulation (~10 s) in CSRm.

Two methods will be used in CSRm to accumulate the heavy ions up to 10^6–10^9 in a short duration of 10 s. One is the Multiple Multi-turn Injection (MMI) in the horizontal phase space with the acceptance of 150π mm mrad. Another is the combination of the horizontal multi-turn injection and the RF Stacking (RFS) [8] in the momentum phase space. In the second method, the horizontal acceptance is 50π mm mrad used for the multi-turn injection and the momentum acceptance is 1.25% for the RFS. During the accumulation, electron cooling will be used for the cooling of beam in order to increase the accumulation ratio and efficiency. Table 3 shows the accumulation parameters of several typical ions.

Table 3
Parameters of the accumulation in CSRm

	O^{7+}	O^{7+}	Xe^{48+}	U^{72+}
Injector	SFC	SFC	SSC	SSC
Energy (MeV/u)	10	10	20	10
Current (e μA)	3	3	0.5	0.05
Current (pps)	2×10^{12}	2×10^{12}	8×10^{10}	8×10^{9}
Particles/turn	8×10^{6}	8×10^{6}	2×10^{5}	3×10^{4}
Efficiency of stripping			19%	15%
Method	RFS	MMI	MMI	MMI
Cycle (ms)	100	2500	250	100
Period (s)	10	10	10	10
Gain factor of MMI	2.8	5	5	5
Particles	2×10^{9}	4×10^{8}	8×10^{6}	2×10^{6}

3.4. Production of secondary beams

RIB will be produced by heavy ion projectile fragmentation (PF) method [9]. The heavy ions from the present HIRFL system will be injected into CSRm for accumulating, cooling and accelerating to higher energies (100–400 MeV/u), and then extracted to bombard a primary target in order to produce radioactive beams. Finally, those RIB produced will be accepted by CSRe for physical experiments with beam cooling.

Highly charged ions, fully stripped heavy ions or H- and He-like heavy ions, are in demand in atomic physics researches. HIRFL-CSR will provide those heavy ion beams by multiple stripping shown in the figure below. In the energy range of CSRe, fully stripped ion as heavy as Gold could be obtained, while the highest charged state for uranium is 91+.

SFC(K=69)--------|----→SSC(k=450)------|-----→CSRm-----|-----→CSRe

(Strip.) Strip. Strip.

$^{238}U^{37+}$ $^{238}U^{37+}$ $^{238}U^{72+}$ $^{238}U^{91+}$

0.96MeV/u 10MeV/u 400MeV/u 400MeV/u

4. Lattice

4.1. CSRm lattice

CSRm has a racetrack shape, as shown in Fig. 4, and consists of four identical arc sections. Each arc section consists of four dipoles, two triplets and one doublet. Eight independent variables for a quadruple are used. The lattice of each arc section is given as follows:

$$\text{-----}\ L_1\text{-----FDF--B--B--F---}\ L_2\text{---DF--B--B--F}\,\frac{1}{2}\,\text{D}$$

where $2L_1$ is a long-straight section with dispersion free for e-cooler or RF cavity. L_2 is a dispersion drift for beam injection or extraction. Fig. 5 denotes the distribution of β-functions and dispersion in CSRm, Table 4 presents the lattice parameters of CSRm.

In the injection arc-section, three bump magnets (BP1, BP2, BP3) will be used to move the closed orbit from the center to the injection position in the horizontal plane, then injection beam will be deflected into the closed orbit by one static-electric septum (ES1) and one magnetic septum (MS1). During the multi-turn injection, the field of the three bumps will be reduced to zero isochronously,

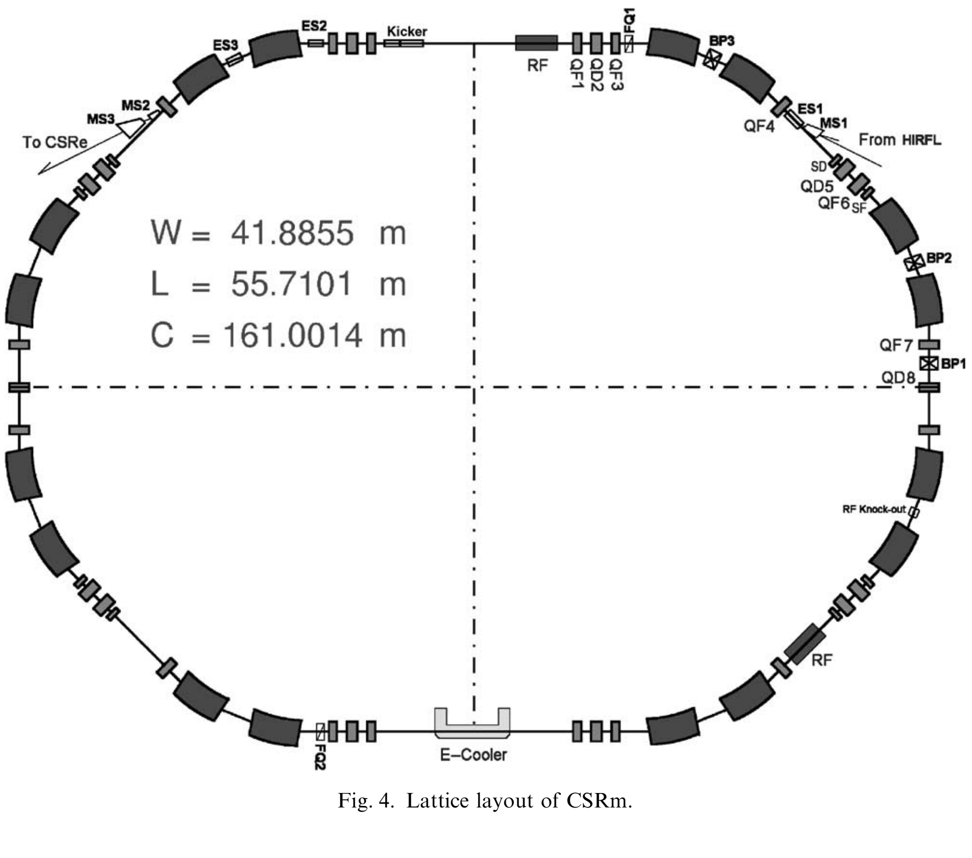


Fig. 4. Lattice layout of CSRm.

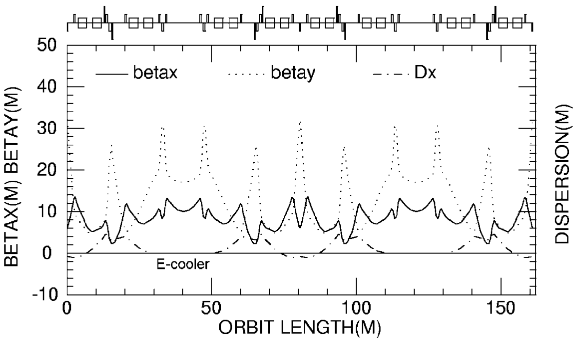


Fig. 5. Distributions of the β and dispersion of CSRm.

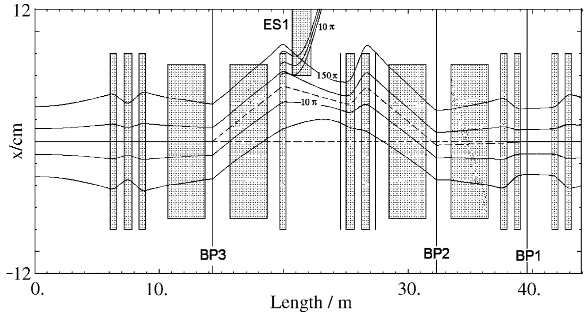


Fig. 6. Orbits of the MMI in CSRm.

Table 4
Lattice parameters of CSRm

Transition gamma	$\gamma_{tr} = 5.168$
Betatron tune values	$Q_x/Q_y = 2.63/2.61$
Natural chromaticity	$Q'_x/Q'_y = -3.05/-5.34$
Max. β-amplitude	$\beta_x/\beta_y = 10.4/17.5$ m (dipole) $\beta_x/\beta_y = 13.5/32.2$ m (quadruple)
Max. dispersion	$D_{max}(x) = 3.2$ m (dipole, $\beta_x = 10.4$ m) $D_{max}(x) = 4.6$ m (Quadruple, $\beta_x = 8.0$ m)
Injection section	$\beta_x = 10.0$ m, $D_x = 4.0$ m (septum) $\beta_x = 11.9$ m, $D_x = 3.9$ m (quadruple)
e-Cooler section	$\beta_x/\beta_y = 10.0/17.0$ m, $D_x = 0$
RF station section	$\beta_x/\beta_y = 10.0/6.4$ m, $D_x = 4.0$

the closed orbit will move back to the center, and the horizontal acceptance ($150\,\pi$ or $50\,\pi$ mm mrad) will be filled by injection beam simultaneously. Fig. 6 depicts the orbit of the MMI.

For CSRm, fast and slow beam extractions should be carried out. In the extraction arc-section, five kicker modes will be used for the fast extraction, and two static-electric septa (ES2, ES3), two fast quadruples (FQ1, FQ2), two families of sextuple and six in-dipole coils will be used for the slow extraction of $\frac{1}{3}$ order resonance. The two extractions will use one channel, and the final elements of the extraction are two magnetic septa (MS2, MS3).

For beam injection and extraction, the special vacuum chambers will be adopted to obtain large horizontal space.

In CSRm, 16 auxiliary coils in dipoles, two combined vertical and horizontal correctors and nine vertical correctors will be used for the global closed-orbit correction.

4.2. CSRe lattice

The layout of CSRe is shown in Fig. 7. It has a racetrack shape and consists of two quasi-symmetric parts. One is the internal-target part and another is the e-cooler part. Each part has a symmetric system and consists of two identical arc sections. Each arc section consists of four dipoles, two triplets or one triplet and one doublet. 11 independent variables for quadruple are used in CSRe. The lattice of the half ring is given as follows:

-- L_T --FD-F--B-B- L_R -FD-F-B-B--B-B-F-DF- L_R -B-B--FD-- L_C --

where $2L_T$ and $2L_C$ are the long-straight sections with dispersion free for internal target and e-cooler. L_R is the dispersion drift for RF cavities.

In CSRe, three lattice modes will be adopted for different requirements. The first one is the internal-target mode with small β-amplitude in target point and the large transverse acceptance (A_h= $150\,\pi$ mm mrad, A_v= $75\,\pi$ mm mrad) for internal-target experiments. The second one is the normal mode with a large momentum acceptance of $\Delta P/P = 2.6\%$ for high-precision mass spectroscopy [10]. The third one is the isochronous mode with a small transition γ_{tr} that equals the energy γ of beam in order to measure the mass of those short-lifetime RIB [11].

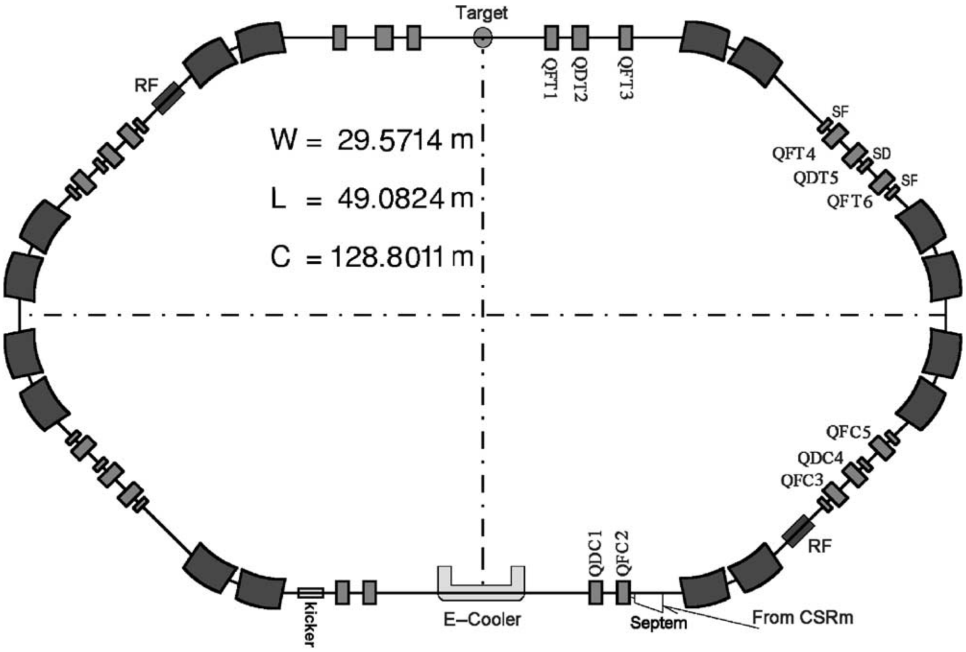


Fig. 7. Lattice layout of CSRe.

Table 5 shows the lattice parameters of CSRe for the three lattice modes, and Figs. 8–10 denotes the distributions of the β-functions and the dispersions for those modes.

The injection of CSRe is located in the zero-dispersion section of the e-cooler in order to accept the large momentum-spread ($\pm 1\%$) beams from RIBLL2 shown in Fig. 1. The single-turn injection will be adopted by using one magnetic septum and four kicker modes. During the injection, four auxiliary coils in four main dipoles will be used to create the bump orbit for the injection, and the injection channel will pass through the fringe field of a dipole and two quadruples. For the three lattice modes, the gradient of the doublet quadruple near the injection septum should be maintained at the same value in order to obtain the same injection orbit. Fig. 11 shows the single-turn injection orbit of CSRe.

In CSRe, two families of sextuple will be used to correct the chromaticity, and 16 in-dipole coils, four double-direction correctors, six vertical correctors will be used for the global closed-orbit correction.

5. Subsystem [12]

5.1. Magnets and correlative subsystems

All the magnetic cores of CSR will be laminated by 0.5 mm-thick sheets of electro-technical steel with high induction and cold-rolled isotropy. Coils will be made of T2 copper conductor with hollow and insulated polyimide stick tape, impregnated with vacuum epoxy resin. In order to reach the necessary field uniformity at the different levels of the range of 1000–14,000 Gs, a so-called modified H-type dipole was designed for CSRm. An air hole will be punched at the center of the pole to control the magnetic field flux flow at high magnetic fields [13]. The magnetic field distribution on the median plane will be improved and a good field distribution in a wide field range can be obtained. In CSRe, the C-type dipole with a large useful aperture will be adopted for physics experiments.

All the power supplies for the ring magnets will need DC and pulse operation modes, while high current stability, low current ripple, good dynamic characteristic are necessary requirements. Two

Table 5
Lattice parameters of CSRe

	Internal-target mode	Normal mode	Isochronous mode
Transition gamma	$\gamma_{tr} = 2.457$	$\gamma_{tr} = 2.629$	$\gamma_{tr} = 1.395$
Betatron tune values	$Q_x/Q_y = 2.53/2.57$	$Q_x/Q_y = 2.53/2.57$	$Q_x/Q_y = 1.695/2.72$
Natural chromaticity	$Q'_x/Q'_y = -3.70/-3.55$	$Q'_x/Q'_y = -3.10/-3.74$	$Q'_x/Q'_y = -1.57/-3.25$
Max. β-amplitude	$\beta_x/\beta_y = 25.7/8.7\,\text{m}$ (dipole) $\beta_x/\beta_y = 43.0/20.4\,\text{m}$ (quadruple)	$\beta_x/\beta_y = 17.6/8.2\,\text{m}$ (dipole) $\beta_x/\beta_y = 30.9/22.3\,\text{m}$ (quadruple)	$\beta_x/\beta_y = 28.1/12.2\,\text{m}$ (dipole) $\beta_x/\beta_y = 41.2/36.4\,\text{m}$ (quadruple)
Max. dispersion	$D_{\max}(x) = 7.9\,\text{m}$ (dipole, $\beta_x = 14\,\text{m}$) $D_{\max}(x) = 9.4\,\text{m}$ (quadruple, $\beta_x = 16\,\text{m}$)	$D_{\max}(x) = 6.5\,\text{m}$ (dipole, $\beta_x = 13\,\text{m}$) $D_{\max}(x) = 7.8\,\text{m}$ (quadruple, $\beta_x = 16\,\text{m}$)	$D_{\max}(x) = 18.5\,\text{m}$ (dipole, $\beta_x = 28\,\text{m}$) $D_{max}(x) = 21.2\,\text{m}$(quadruple, $\beta_x = 34\,\text{m}$)
Injection section	$\beta_x = 30.8\,\text{m}$, $D_x = 0\,\text{m}$ (septum) $\beta_x = 31.4\,\text{m}$, $D_x = 0\,\text{m}$ (quadruple)	$\beta_x = 30.4\,\text{m}$, $D_x = 0\,\text{m}$ (septum) $\beta_x = 30.9\,\text{m}$, $D_x = 0\,\text{m}$ (quadruple)	$\beta_x = 40.8\,\text{m}$, $D_x = 0\,\text{m}$ (septum) $\beta_x = 41.2\,\text{m}$, $D_x = 0\,\text{m}$ (quadruple)
e-Cooler section	$\beta_x/\beta_y = 12.9/16.5\,\text{m}$, $D_x = 0$	$\beta_x/\beta_y = 12.5/16.0\,\text{m}$, $D_x = 0$	$\beta_x/\beta_y = 2.6/10.5\,\text{m}$, $D_x = 0$
Target	$\beta_x/\beta_y = 3.0/1.7\,\text{m}$, $D_x = 0$	$\beta_x/\beta_y = 5.4/1.5\,\text{m}$, $D_x = 0$	$\beta_x/\beta_y = 20.8/1.0\,\text{m}$, $D_x = 17.7\,\text{m}$
RF station section	$\beta_x/\beta_y = 4.0/8.3\,\text{m}$, $D_x = 4.6$	$\beta_x/\beta_y = 4.0/8.4\,\text{m}$, $D_x = 4.5$	$\beta_x/\beta_y = 19.0/11.5\,\text{m}$, $D_x = 15.0\,\text{m}$

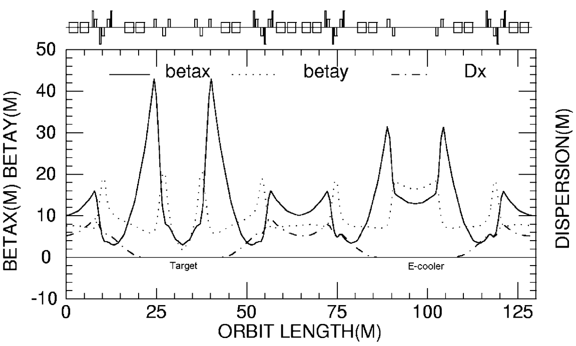


Fig. 8. Distribution of the β-functions and dispersion for the internal-target mode.

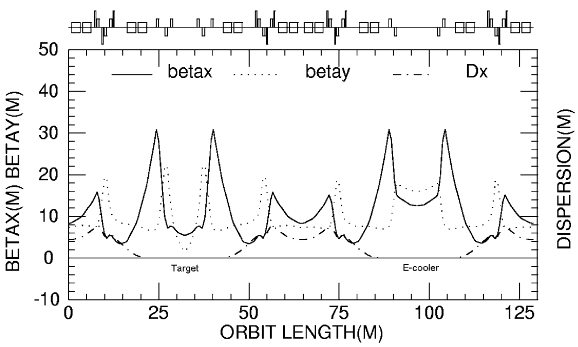


Fig. 9. Distribution of the β-functions and dispersion for the normal mode.

types of supply, a traditional multi-phase thyristor rectifier for dipoles and a switching mode convertor for quadruples, will be adopted.

Table 6 displays the major parameters of magnets and its correlative power supplies and vacuum chambers.

5.2. Electron-cooler system

Two electron coolers will be equipped in CSRm and CSRe, respectively, for heavy ion beam cooling. In CSRm, e-cooling will be used for the beam accumulation at the injection energy range of 8–30 MeV/u to increase the beam intensity. In CSRe, e-cooling will be used to compensate the growth of beam emittance during internal-target experiments or to provide high-quality beams for the high-resolution mass measurements [10] of nuclei. Table 7 denotes the major parameters of the two e-coolers, and Figs. 12 and 13 are the general view of them. The two coolers are similar with the only difference in the high voltage unit in

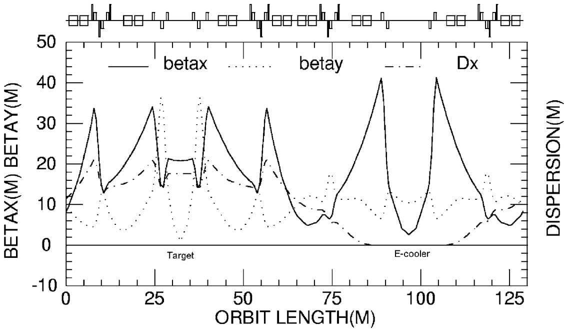


Fig. 10. Distribution of the β-functions and dispersion for the isochronous mode.

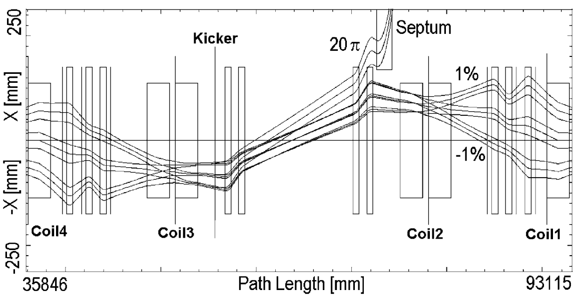


Fig. 11. Single-turn injection orbit of CSRe.

order to reduce the time of the development and the production cost of the devices.

5.3. RF system

Two RF cavities will be used for the accelerating beam and RFS in CSRm, respectively. The stacking cavity with the frequency range of 6.0–14.0 MHz will be used to secure the SSC or SFC beam bunches with harmonic number $h = 16$, 32 or 64 during the beam accumulation in the momentum acceptance. After beam accumulation, the heavy ion beams will be accelerated by the accelerating cavity from the low energy range of 8–30 MeV/u to the high-energy range of 100–900 MeV/u with harmonic number $h = 1$. In CSRe, two identical RF cavities will be installed in two drift sections, which will be used for beam capture, bunching, de-bunching and deceleration with harmonic number $h = 1$ or 2.

The four RF cavities are ferrite-loaded coaxial resonators, and the resonance frequency is controlled by tuning the magnetic biasing current of ferrite. Table 8 displays the general parameters of the CSR RF system.

Table 6
Major correlative parameters of the magnets

	CSRm	CSRe
Dipole		
Number × angle (deg.)	16×22.5	16×22.5
Bending radius (m)	7.6	6.0
Field range (T)	0.1–1.4	0.1–1.4
Ramping rate (T/s)	0.1–0.4	0.1–0.4
Air gap (mm)	80	95
Useful aperture (mm^2)	140×60	220×70
Homogeneity ($\Delta B/B$)	$\pm 1.5 \times 10^{-4}$	$\pm 1.5 \times 10^{-4}$
Vacuum chamber		
Aperture (mm^2)	156×61	236×74
Cross-section	Rectangular	Rectangular
Supply of dipole		
Number	1	1
Feeding mode	Series	Series
Stability (at low cur.)	$\pm 1 \times 10^{-4}$/8 h	$\pm 1 \times 10^{-4}$/8 h
Ripple (at low cur.)	5×10^{-5}	5×10^{-5}
Tracking precision	$\pm 3 \times 10^{-4}$	$\pm 3 \times 10^{-4}$
Quadruple		
Number	30	22
Gradient range (T/m)	0.3—9.0	0.3–6.5
Bore diameter (mm)	170	240
Useful aperture (mm^2)	160×100	280×140
$\Delta K/K$	$\pm 1.5 \times 10^{-3}$	$\pm 1.5 \times 10^{-3}$
Ideal length (m)	0.5, 0.65	0.65, 0.75
Vacuum chamber		
Aperture (mm^2)	188×116	285×150
Cross-section	Octagonal	Octagonal
Supply of quadruple		
Number	30	22
Feeding mode	Independent	Independent
Stability (at low cur.)	$\pm 1 \times 10^{-4}$/8 h	$\pm 1 \times 10^{-4}$/8 h
Ripple (at low cur.)	5×10^{-5}	5×10^{-5}
Tracking precision	$\pm 5 \times 10^{-4}$	$\pm 5 \times 10^{-4}$

5.4. Ultra-high vacuum system

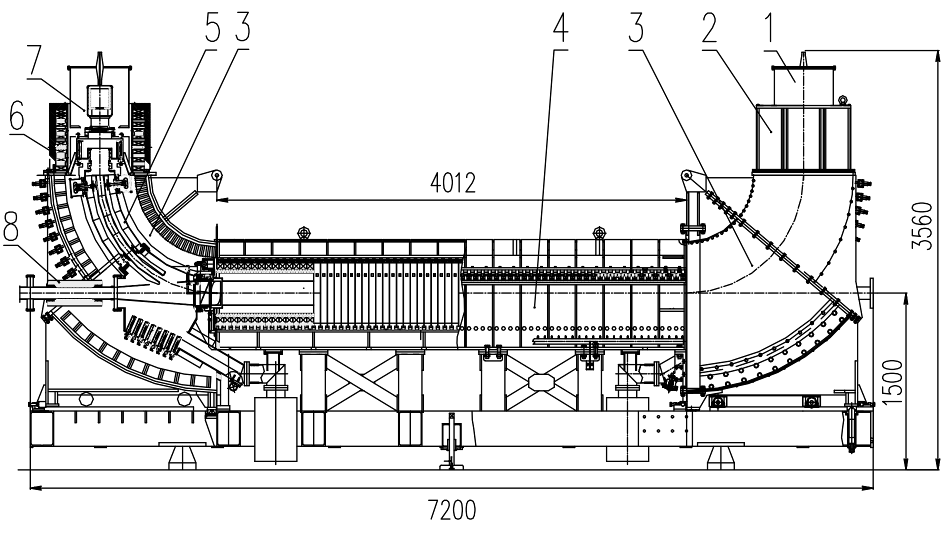
The vacuum system is divided into four parts, the two storage rings of CSRm and CSRe, and the

Table 7
Major parameters of the two e-coolers

Parameters	CSRm	CSRe
Ion energy (MeV/u)	8–50	25–400
Electron energy (keV)	4–35	10–300
Max. electron current (A)	3	3
Cathode radius (cm)	1.25	1.25
Magnetic expansion factor	1–4	1–10
Max. field of gun region (kG)	2.4	5
Magnetic field of collector region (kG)	1.2	1.2
Magnetic field of cooling section (kG)	0.6–1.5	0.5–1.5
Length of cooling section (m)	4.0 (effective length = 3.4 m)	4.0 (effective length = 3.4 m)
Installation length (m)	7.2	7.2
Deflection angle of toroid (deg.)	90°	90°
Deflection radius of toroid (m)	1.0	1.0

two beam lines of the injection line from HIRFL, and RIBLL2. The pressure of $<6\times10^{-11}$ mbar (N2 equivalent) will be required in CSRm and CSRe, and 1×10^{-9} mbar will be necessary for the two beam lines.

For CSR UHV system, titanium sublimation pump and sputter ion pump are chosen as the main pumps, and about 160 titanium pumps and 85 ion pumps will be equipped in CSR. For each part, two or three movable oil-free turbo-molecular pumping station will be equipped for pre-pumping, leak detecting and back out. Many all-metal gate valves will be used to divide each part into several sections, and fast-closed valves will also be installed in injection and extraction positions for protecting the two rings from possible accidents. A lot of bellows with the length of 0.2–0.28 m will be installed at those possible positions, specially the two sides of the dipole chambers, in order to correct installation error and absorb the heat expansion during the bake-out process.

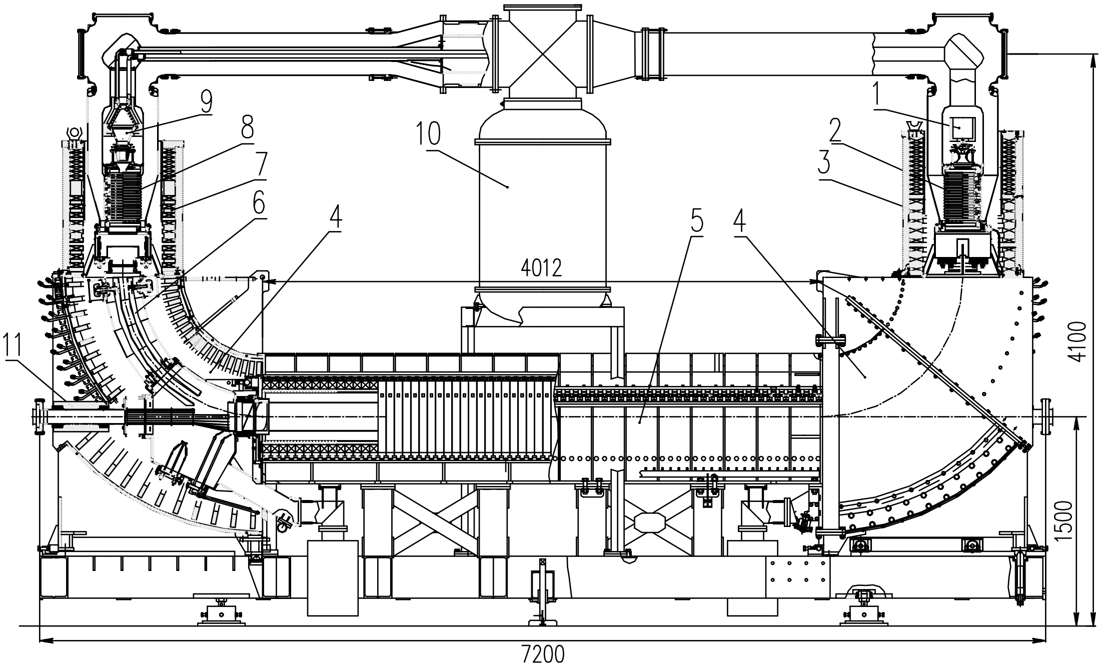


1- Electron gun, 2- The solenoid of the gun, 3-Toroid, 4- Main solenoid,

5- Electrostatic deflector, 6- The solenoid of the collector, 7- Collector,

8- Dipole corrector.

Fig. 12. Layout of the CSRm e-cooler.



1- Electron gun, 2- Accelerating tube, 3- The solenoid of the gun , 4-Toroid,

5-Main solenoid, 6- Electrostatic deflector, 7- The solenoid of the collector,

8- Decelerating tube, 9- Collector, 10- 300KV-HV System, 11- Dipole corrector.

Fig. 13. Layout of the CSRe e-cooler.

Table 8
General parameters of the CSR RF cavities

Cavity	Acceleration in CSRm	Stacking in CSRm	Deceleration in CSRe
Number of cavity	1	1	2
Freq. range (MHz)	0.24–1.7	6.0–14.0	0.5–2.0
Harmonic number	1	16, 32, 64	1, 2
Peak RF voltage (kV)	7.0	20	20
Peak RF power (kW)	18	20	30
Installation length (m)	2.6	2.1	2.0
Aperture ϕ (mm)	200	200	200
Gap capacitance (pf)	6800	190–1300	2000

The vacuum bake-out temperature will be 300°C. And all the components of the two rings will be equipped with permanent back-out jackets. The dipole and quadruple chambers will be heated by coaxial heaters with an out-diameter of 2 mm. A special insulation material (Microtherm) will be used for these chambers to avoid thermal loss and protect the magnet coils from damage. This insulation will keep the outside temperature lower than 80°C with the thickness of 3–5 mm. Other chambers are baked by heating tapes which are made of glass fiber with the thickness of 10–25 mm.

5.5. Beam diagnosis system

For the CSR beam diagnosis, the standard synchrotron and cooling ring instrumentation is to be used and has to be developed to cover the wide range of beam characteristics. In each ring, two or three viewing screens and one Faraday-cup will be used for the first-turn tuning, one combined vertical and horizontal Schottky detector, one phase pick-up and two beam transformers will be used for the machine operation, one magnesium jet monitor will be used to detect the beam profile, and 14 or 10 position pick-ups will be equipped for the global closed-orbit correction in the two transverse planes. In beam lines, only viewing screen and Faraday-cup will be used.

5.6. Internal-target system

The CSRe internal target is designed to provide both polarized and unpolarized atomic jets for physics experiments. In the target source of the polarized mode, sextuple magnets will be used to get the high-polarized H or D atomic jets with the expected spin state, and after the state selection in multiple magnets a desired jet density of 5×10^{11} atoms/cm^2 will be obtained. In the normal unpolarized mode, the jet is a cluster jet and the density of 1×10^{12} atoms/cm^2 can be achieved by cooling the nozzle to the given temperature.

5.7. Survey and alignment

One permanent standard point near the ring center and many normal control-network points in each ring will be used for the survey and alignment. According to the control-networks design, the maximum point-position error of the horizontal control-network should be <0.06 mm, and the vertical one should be <0.05 mm.

For the CSR alignment, the installation errors of magnets should be less than the desired values.

Table 9
Misalignments of dipole and quadruple

Error	Dipole	Quadruple
ΔX (mm)	0.5	0.15
ΔY (mm)	0.5	0.15
ΔZ (mm)	2.0	0.5
$\Delta\phi$ (mrad)	0.5	0.5
$\Delta\theta$ (mrad)	0.5	0.5
$\Delta\psi$ (mrad)	0.5	0.5

According to the error simulation results, the desired misalignments of dipole and quadruple are shown in Table 9, where six misalignments are three position errors, Δx (horizontal), Δy (vertical), Δz (beam direction) and three angle errors, $\Delta\phi$, $\Delta\theta$, $\Delta\psi$ around x-, y-, z-axis, respectively.

In order to meet the requirements of survey and alignment, the traditional optical instruments will be used for the pre-installations, and one laser tracker, a digital-levelling device will be used for the final survey and alignment adjustment.

6. RIBLL2 description

RIBLL2, the second Radioactive Ion Beam Line at Lanzhou, is one of the parts of the beam transport line between CSRm and CSRe, shown in Fig. 1. It is designed to operate at a higher energy with the maximum magnetic rigidity of 10.64 Tm. The separator of RIBLL2, which consists of two dipoles and ten quadruples, is a mirror-symmetric system, achieving a point-point and parallel–parallel image at its intermediate focal plane with maximum position dispersion. The double achromatism of $D = D' = 0$ is automatically realized at the final focal plane. Its resolving power of magnetic rigidity is 1200 at the momentum deviation of $\Delta P/P = \pm 1\%$ and the divergence of ± 25 mrad. Fig. 14 shows the envelope in the x-plane of the separator.

The following part is almost a copy of the separator to further purify RIB. The total length of RIBLL2 is about 55 m. And its ion optics is optimized to a third order in order to obtain high realistic resolving power and to minimize the

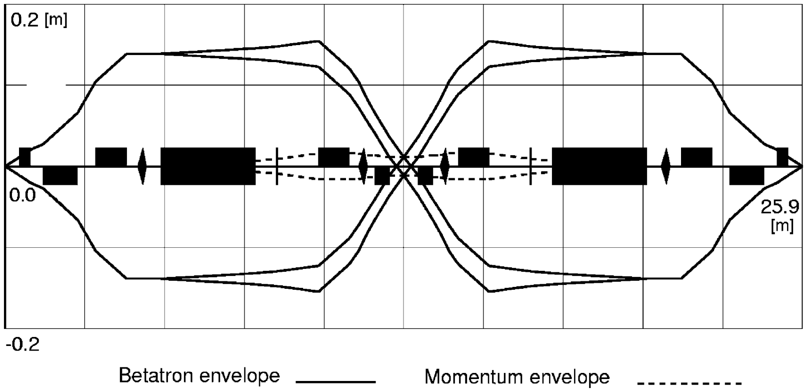


Fig. 14. Horizontal envelope of the RIBLL2 separator with the $\Delta P/P$ of $\pm 1\%$ and emittance of 25π mm mrad.

Table 10
Major parameters of the RIBLL2 magnets

Dipole				
Number	4			
Arc length (mm)	3054			
Bending radius (mm)	7000			
Bending angle (deg.)	25			
Magnet field (T)	1.52			
Useful aperture (mm^2)	320×56			
Quadruple				
Number	4	4	4	8
Length (mm)	400	500	1100	1000
Strength (T/m)	19.02	7.77	12.05	7.58
Aperture (mm^2)	80×80	150×150	150×150	320×110

emittance growth. Table 10 denotes the major parameters of the RIBLL2 magnets.

7. Project status and schedule

The CSR project is similar to the MUSES project at the RIKEN RI beam factory [14] and the SIS-ESR complex at GSI [15]. Many technology co-operations with the two projects are on going. The building construction of CSR was started on December 10, 1999 and finished the summer 2001. In the beginning of 2000, the UHV bake oven was made by a local company. The construction of the injection beam line from HIRFL to CSRm is to be completed by the end of 2001. Several subsystems, two e-coolers, RF system, kickers, internal-target system and the Mg-jet monitors, are being designed and fabricated jointly by IMP and the Russian BINP. The major subsystems, magnet, power supply, vacuum chamber, control, beam diagnosis and so on will be manufactured by several Chinese companies from 2001 to 2003.

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